

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau(43) International Publication Date
28 February 2002 (28.02.2002)

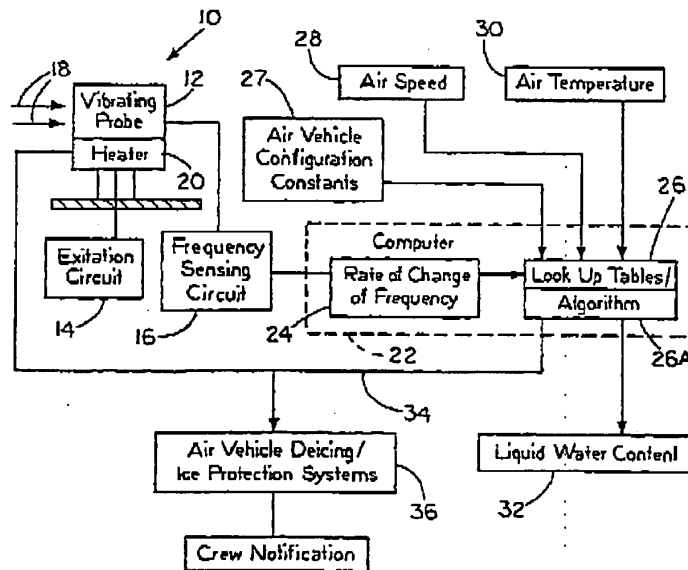
PCT

(10) International Publication Number
WO 02/16201 A1

- (51) International Patent Classification⁷: B64D 15/22 (74) Agents: WESTMAN, Nicholas, E. et al.; Westman, Champlin & Kelly, P.A., Suite 1600 - International Centre, 900 Second Avenue South, Minneapolis, MN 55402-3319 (US).
- (21) International Application Number: PCT/US01/25691
- (22) International Filing Date: 16 August 2001 (16.08.2001)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
09/641,298 18 August 2000 (18.08.2000) US
- (71) Applicant: ROSEMOUNT AEROSPACE INC.
[US/US]; 14300 Judicial Road, Burnsville, MN 55306 (US).
- (72) Inventors: SEVERSON, John, A.; 883 Basswood Lane, Eagan, MN 55123 (US). SCHRAM, Kenneth, J.; 9654 Hampshire Lane, Eden Prairie, MN 55347 (US).
- (81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZW.
- (84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SI, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).
- Published:
— with international search report

[Continued on next page]

(54) Title: LIQUID WATER CONTENT MEASUREMENT APPARATUS AND METHOD



(57) Abstract: Ice accretion on a probe (12) is detected by determining the change of frequency of a vibrating type ice detector or sensor (14, 16) as ice starts to build up. The rate of change of frequency is determined (24) and is combined with parameters including air velocity (28) and air temperature (30) for providing a signal that indicates liquid water content in the airflow as well as ice accretion on the ice detector (14, 16).

WO 02/16201 A1

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039 1040 1041 1042 1043 1044 1045 1046 1047 1048 1049 1050 1051 1052 1053 1054 1055 1056 1057 1058 1059 1060 1061 1062 1063 1064 1065 1066 1067 1068 1069 1070 1071 1072 1073 1074 1075 1076 1077 1078 1079 1080 1081 1082 1083 1084 1085 1086 1087 1088 1089 1090 1091 1092 1093 1094 1095 1096 1097 1098 1099 1100 1101 1102 1103 1104 1105 1106 1107 1108 1109 1110 1111 1112 1113 1114 1115 1116 1117 1118 1119 1120 1121 1122 1123 1124 1125 1126 1127 1128 1129 1130 1131 1132 1133 1134 1135 1136 1137 1138 1139 1140 1141 1142 1143 1144 1145 1146 1147 1148 1149 1150 1151 1152 1153 1154 1155 1156 1157 1158 1159 1160 1161 1162 1163 1164 1165 1166 1167 1168 1169 1170 1171 1172 1173 1174 1175 1176 1177 1178 1179 1180 1181 1182 1183 1184 1185 1186 1187 1188 1189 1190 1191 1192 1193 1194 1195 1196 1197 1198 1199 1200 1201 1202 1203 1204 1205 1206 1207 1208 1209 1210 1211 1212 1213 1214 1215 1216 1217 1218 1219 1220 1221 1222 1223 1224 1225 1226 1227 1228 1229 1230 1231 1232 1233 1234 1235 1236 1237 1238 1239 1240 1241 1242 1243 1244 1245 1246 1247 1248 1249 1250 1251 1252 1253 1254 1255 1256 1257 1258 1259 1260 1261 1262 1263 1264 1265 1266 1267 1268 1269 1270 1271 1272 1273 1274 1275 1276 1277 1278 1279 1280 1281 1282 1283 1284 1285 1286 1287 1288 1289 1290 1291 1292 1293 1294 1295 1296 1297 1298 1299 1300 1301 1302 1303 1304 1305 1306 1307 1308 1309 1310 1311 1312 1313 1314 1315 1316 1317 1318 1319 1320 1321 1322 1323 1324 1325 1326 1327 1328 1329 1330 1331 1332 1333 1334 1335 1336 1337 1338 1339 1340 1341 1342 1343 1344 1345 1346 1347 1348 1349 1350 1351 1352 1353 1354 1355 1356 1357 1358 1359 1360 1361 1362 1363 1364 1365 1366 1367 1368 1369 1370 1371 1372 1373 1374 1375 1376 1377 1378 1379 1380 1381 1382 1383 1384 1385 1386 1387 1388 1389 1390 1391 1392 1393 1394 1395 1396 1397 1398 1399 1400 1401 1402 1403 1404 1405 1406 1407 1408 1409 1410 1411 1412 1413 1414 1415 1416 1417 1418 1419 1420 1421 1422 1423 1424 1425 1426 1427 1428 1429 1430 1431 1432 1433 1434 1435 1436 1437 1438 1439 1440 1441 1442 1443 1444 1445 1446 1447 1448 1449 1450 1451 1452 1453 1454 1455 1456 1457 1458 1459 1460 1461 1462 1463 1464 1465 1466 1467 1468 1469 1470 1471 1472 1473 1474 1475 1476 1477 1478 1479 1480 1481 1482 1483 1484 1485 1486 1487 1488 1489 1490 1491 1492 1493 1494 1495 1496 1497 1498 1499 1500 1501 1502 1503 1504 1505 1506 1507 1508 1509 1510 1511 1512 1513 1514 1515 1516 1517 1518 1519 1520 1521 1522 1523 1524 1525 1526 1527 1528 1529 1530 1531 1532 1533 1534 1535 1536 1537 1538 1539 1540 1541 1542 1543 1544 1545 1546 1547 1548 1549 1550 1551 1552 1553 1554 1555 1556 1557 1558 1559 1560 1561 1562 1563 1564 1565 1566 1567 1568 1569 1570 1571 1572 1573 1574 1575 1576 1577 1578 1579 1580 1581 1582 1583 1584 1585 1586 1587 1588 1589 1590 1591 1592 1593 1594 1595 1596 1597 1598 1599 1600 1601 1602 1603 1604 1605 1606 1607 1608 1609 1610 1611 1612 1613 1614 1615 1616 1617 1618 1619 1620 1621 1622 1623 1624 1625 1626 1627 1628 1629 1630 1631 1632 1633 1634 1635 1636 1637 1638 1639 1640 1641 1642 1643 1644 1645 1646 1647 1648 1649 1650 1651 1652 1653 1654 1655 1656 1657 1658 1659 1660 1661 1662 1663 1664 1665 1666 1667 1668 1669 1670 1671 1672 1673 1674 1675 1676 1677 1678 1679 1680 1681 1682 1683 1684 1685 1686 1687 1688 1689 1690 1691 1692 1693 1694 1695 1696 1697 1698 1699 1700 1701 1702 1703 1704 1705 1706 1707 1708 1709 1710 1711 1712 1713 1714 1715 1716 1717 1718 1719 1720 1721 1722 1723 1724 1725 1726 1727 1728 1729 1730 1731 1732 1733 1734 1735 1736 1737 1738 1739 1740 1741 1742 1743 1744 1745 1746 1747 1748 1749 1750 1751 1752 1753 1754 1755 1756 1757 1758 1759 1760 1761 1762 1763 1764 1765 1766 1767 1768 1769 1770 1771 1772 1773 1774 1775 1776 1777 1778 1779 1780 1781 1782 1783 1784 1785 1786 1787 1788 1789 1790 1791 1792 1793 1794 1795 1796 1797 1798 1799 1800 1801 1802 1803 1804 1805 1806 1807 1808 1809 1810 1811 1812 1813 1814 1815 1816 1817 1818 1819 1820 1821 1822 1823 1824 1825 1826 1827 1828 1829 1830 1831 1832 1833 1834 1835 1836 1837 1838 1839 1840 1841 1842 1843 1844 1845 1846 1847 1848 1849 1850 1851 1852 1853 1854 1855 1856 1857 1858 1859 1860 1861 1862 1863 1864 1865 1866 1867 1868 1869 1870 1871 1872 1873 1874 1875 1876 1877 1878 1879 1880 1881 1882 1883 1884 1885 1886 1887 1888 1889 1890 1891 1892 1893 1894 1895 1896 1897 1898 1899 1900 1901 1902 1903 1904 1905 1906 1907 1908 1909 1910 1911 1912 1913 1914 1915 1916 1917 1918 1919 1920 1921 1922 1923 1924 1925 1926 1927 1928 1929 1930 1931 1932 1933 1934 1935 1936 1937 1938 1939 1940 1941 1942 1943 1944 1945 1946 1947 1948 1949 1950 1951 1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070 2071 2072 2073 2074 2075 2076 2077 2078 2079 2080 2081 2082 2083 2084 2085 2086 2087 2088 2089 2090 2091 2092 2093 2094 2095 2096 2097 2098 2099 2100 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114 2115 2116 2117 2118 2119 2120 2121 2122 2123 2124 2125 2126 2127 2128 2129 2130 2131 2132 2133 2134 2135 2136 2137 2138 2139 2140 2141 2142 2143 2144 2145 2146 2147 2148 2149 2150 2151 2152 2153 2154 2155 2156 2157 2158 2159 2160 2161 2162 2163 2164 2165 2166 2167 2168 2169 2170 2171 2172 2173 2174 2175 2176 2177 2178 2179 2180 2181 2182 2183 2184 2185 2186 2187 2188 2189 2190 2191 2192 2193 2194 2195 2196 2197 2198 2199 2200 2201 2202 2203 2204 2205 2206 2207 2208 2209 2210 2211 2212 2213 2214 2215 2216 2217 2218 2219 2220 2221 2222 2223 2224 2225 2226 2227 2228 2229 2230 2231 2232 2233 2234 2235 2236 2237 2238 2239 2240 2241 2242 2243 2244 2245 2246 2247 2248 2249 2250 2251 2252 2253 2254 2255 2256 2257 2258 2259 2260 2261 2262 2263 2264 2265 2266 2267 2268 2269 2270 2271 2272 2273 2274 2275 2276 2277 2278 2279 2280 2281 2282 2283 2284 2285 2286 2287 2288 2289 2290 2291 2292 2293 2294 2295 2296 2297 2298 2299 2300 2301 2302 2303 2304 2305 2306 2307 2308 2309 2310 2311 2312 2313 2314 2315 2316 2317 2318 2319 2320 2321 2322 2323 2324 2325 2326 2327 2328 2329 2330 2331 2332 2333 2334 2335 2336 2337 2338 2339 2340 2341 2342 2343 2344 2345 2346 2347 2348 2349 2350 2351 2352 2353 2354 2355 2356 2357 2358 2359 2360 2361 2362 2363 2364 2365 2366 2367 2368 2369 2370 2371 2372 2373 2374 2375 2376 2377 2378 2379 2380 2381 2382 2383 2384 2385 2386 2387 2388 2389 2390 2391 2392 2393 2394 2395 2396 2397 2398 2399 2400 2401 2402 2403 2404 2405 2406 2407 2408 2409 2410 2411 2412 2413 2414 2415 2416 2417 2418 2419 2420 2421 2422 2423 2424 2425 2426 2427 2428 2429 2430 2431 2432 2433 2434 2435 2436 2437 2438 2439 2440 2441 2442 2443 2444 2445 2446 2447 2448 2449 2450 2451 2452 2453 2454 2455 2456 2457 2458 2459 2460 2461 2462 2463 2464 2465 2466 2467 2468 2469 2470 2471 2472 2473 2474 2475 2476 2477 2478 2479 2480 2481 2482 2483 2484 2485 2486 2487 2488 2489 2490 2491 2492 2493 2494 2495 2496 2497 2498 2499 2500 2501 2502 2503 2504 2505 2506 2507 2508 2509 2510 2511 2512 2513 2514 2515 2516 2517 2518 2519 2520 2521 2522 2523 2524 2525 2526 2527 2528 2529 2530 2531 2532 2533 2534 2535 2536 2537 2538 2539 2540 2541 2542 2543 2544 2545 2546 2547 2548 2549 2550 2551 2552 2553 2554 2555 2556 2557 2558 2559 2560 2561 2562 2563 2564 2565 2566 2567 2568 2569 2570 2571 2572 2573 2574 2575 2576 2577 2578 2579 2580 2581 2582 2583 2584 2585 2586 2587 2588 2589 2590 2591 2592 2593 2594 2595 2596 2597 2598 2599 2600 2601 2602 2603 2604 2605 2606 2607 2608 2609 2610 2611 2612 2613 2614 2615 2616 2617 2618 2619 2620 2621 2622 2623 2624 2625 2626 2627 2628 2629 2630 2631 2632 2633 2634 2635 2636 2637 2638 2639 2640 2641 2642 2643 2644 2645 2646 2647 2648 2649 2650 2651 2652 2653 2654 2655 2

-1-

LIQUID WATER CONTENT MEASUREMENT

APPARATUS AND METHOD

BACKGROUND OF THE INVENTION

The present invention relates to an apparatus and method for determining with accuracy the liquid water content of ambient air, particularly in relation to air flows across air vehicles or other structures. The accurate and timely measurement of liquid water content (LWC) permits prompt signalling for activating deicing systems, and also permits sensing atmospheric conditions for reporting or research purposes.

Unheated bodies exposed to airflow laden with supercooled water droplets will typically accrete ice as the droplets impact the body and freeze. Icing is particularly a problem with air vehicles. Determining when ice is starting to form or predicting when it will form is important in aircraft management of deicing equipment including heaters, which can consume huge amounts of power. When the air temperature is cold enough, 100% of the droplets carried in the airflow will freeze. If the temperature warms or airflow is increased, the energy balance relationship is altered. A critical liquid water content (LWC) is reached where not all of the impinging supercooled water droplets freeze. This critical LWC is defined as the Ludlam Limit. The Ludlam Limit is described in an article by F.H. Ludlam entitled The Heat Economy of a Rimed Cylinder. Quart. J. Roy. Met. Soc., Vol. 77, 1951, pp. 663-666. Additional descriptions of the problem are in articles by B.L. Messinger, entitled Equilibrium Temperature of an Unheated Icing Surface as a Function of Air Speed,

-2-

Journal of the Aeronautical Sciences, January 1953,
and a further article entitled An Appraisal of The
Single Rotating Cylinder Method of Liquid Water
Content Measurement, by J.R. Stallbrass, Report - Low
5 Temperature Laboratory No. LTR-LT-92, National
Research Council, Canada, 1978.

It has been shown that if the LWC increases
above the Ludlam Limit, the accretion characteristics
in theory remain unchanged, because excess water
10 simply blows off or runs off, rather than freezing.
Thus, present systems for determining liquid water
content based on ice accretion suffer degraded
accuracy above the Ludlam Limit. The Ludlam Limit for
a given temperature and airflow is the liquid water
15 content above which not all of the water freezes on
impact with an accreting surface.

Accretion based ice detectors are frequently
designed with probes that permit ice build up to a set
mass, perhaps taking 30 to 60 seconds depending on
20 conditions, at which time the presence of ice is
enunciated or indicated, and a probe heater energized
to melt the ice. Such ice detectors are well known in
the art, and many depend upon a vibrating sensor or
probe, with a frequency sensitive circuit set to
25 determine frequency changes caused by ice accreting on
the detector probe.

LWC can be roughly determined by monitoring
a signal proportional to the probe icing rate, which
again can be determined with existing circuitry, but
30 accuracy degrades rapidly if the LWC is above the
Ludlam Limit, because a portion of the impinging water
never freezes. In such cases the actual LWC will be
under reported, with the Ludlam Limit LWC being the

-3-

maximum that will be reported. Even though the droplet cloud may contain additional liquid water, there will be no indication from such an ice detector that there is additional liquid water in the air flow.

- 5 Thus, the prior art devices will not discern the actual liquid water content when the Ludlam Limit has been exceeded.

SUMMARY OF THE INVENTION

- The present invention relates to determining
- 10 the liquid water content (LWC) in an airflow, in particular, air flow past an air data sensing probe on an air vehicle. The amount of the liquid water in the airflow is determined even for liquid water content levels above the Ludlam Limit. The present invention
- 15 senses ice growth rate on a vibrating probe type ice detector. The ice growth rate is predictably variable over an accretion cycle based upon the incremental rate of change of the vibrating probe's frequency throughout the sensing cycle. The rate of change of
- 20 probe vibration frequency (df/dt) throughout the ice accretion cycle is determined. Further, the rate of frequency change (df/dt) characteristics are demonstrated to be a predictable function of liquid water content, even above the Ludlam Limit, meaning
- 25 that LWC can be determined at the higher liquid water content level.

- The rate of change of probe vibrating frequency is determined for all or a portion of the ice accretion phase of the probe operating cycle,
- 30 because it has been determined that this rate of frequency change (df/dt) is a function of LWC at that time.

In order to measure liquid water content

-4-

with the present invention, the air speed and the temperature of the ambient air must be known. These basic parameters are readily available from an air data computer, using outside instrumentation, such as a pitot tube or a pitot-static tube, and a temperature sensor, such as a total air temperature sensor. The known liquid water content at a particular known air speed, temperature and rate of change of the vibration frequency of a vibrating probe ice detector are determined and combined in a look up table. The values can be determined by actual icing wind tunnel tests, or test results can be used to derive an algorithm that provides liquid water content when the three variables, air flow rate (or air speed), temperature and rate of change of frequency of vibration caused by ice accretion are known. Although a frequency rate of change is described herein, the rate of change of other signals sensitive to ice accretion could be used. A signal based on the rate of change of ice accretion (but not merely the amount of ice accretion) is a key to proper results.

The overall accretion time has been found to decrease with increasing liquid water content in most cases, but this is not assured. This invention is dependent on ice accretion, and will approach some limit of usefulness when operating conditions are such that little or no ice accretes on the probe. This may occur under conditions of warmer air temperature and high aerodynamic heating, for example.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic block diagram of the apparatus used for determining liquid water content (LWC) in response to rate of change of frequency

-5-

caused by commencement of ice accretion on a vibrating probe and for controlling probe heater deicers;

Figure 2 is a plot of measured rate of change or frequency during ice accretion at -5°C temperature, with a constant air speed of 200 knots with airflows having three different, but known levels of liquid water content in the air flow;

Figure 3 is a plot similar to Figure 2 with the indications taken at -10°C and a constant air speed of 200 knots with the same liquid water content in the airflows;

Figure 4 is a plot of rate of change of frequency during ice accretion of a typical vibrating probe at -5°C and a speed of 100 knots; and

Figure 5 is a composite plot of points derived as an average of several rate of change of frequency values (df/dt) of a test probe as a function of liquid water content at different air speeds and temperatures.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS

Figure 1 illustrates a typical set up for utilization of an existing ice detecting probe and the circuitry for determining liquid water content (LWC) even above the Ludlam Limit. The apparatus includes a vibrating ice collecting or detector probe 12, such as that sold by Rosemount Aerospace Inc., Burnsville, Minnesota, as its Model 0871 series. An early vibrating, resonant frequency ice detector probe is shown in U.S. Patent No. 3,341,835 to F.D. Werner et al. In the present invention, an excitation circuit 14 is used for providing an excitation signal to vibrate the vibrating probe at a resonant frequency. A known frequency sensing circuit 16 is

-6-

utilized for determining changes of frequency of the vibrating ice detector probe in a conventional manner.

The change in frequency is caused by ice accretion on the surface of the ice detector probe. This design is
5 recognized to be insensitive to probe contaminants such as dirt and insects. The rate of accretion of ice is reflected in the rate of change of frequency. The rate of ice accretion is directly related to the liquid water content of the air. The probe 12 is
10 exposed to airflow as indicated by the arrows 18, and supercooled water droplets will impact and freeze on the probe 12 surface or previously accreted ice at surface temperatures below freezing. The signal 34 indicating ice formation can be used for turning on
15 deicing equipment 36 or other ice protection systems for the air vehicle involved and/or notifying the crew of an icing condition. The signal 34 indicating ice formation can be tailored to the particular air vehicle and its level of tolerance for ice buildup,
20 such that deicing equipment is activated in a timely manner, while nuisance activations are minimized.

The look up tables 26 or algorithm 26A are designed to determine an icing severity level. After a predetermined duration of exposure at a particular
25 icing condition constituting an icing severity level, or an aggregate of conditions resulting in equivalent ice buildup or impact to the aircraft, the signal 34 is supplied. The signal may be supplied continually or on a periodic basis until the icing condition
30 abates. The calculated df/dt value changes and provides the indication of ice formation, and when correlated to airspeed and temperature is used as the measured parameter for turning on deicing heaters and

-7-

determining LWC. The heaters indicated at 20 that are associated with the ice detector probe, for removing the ice that has built up on the probe during the operational cycle, may also be activated with this signal. The advantage is that reset times may be faster than current practice of deicing the probe after a set mass of ice has accreted.

In the present invention, the frequency sensing circuit 16 provides an indication of the change of frequency of the probe 12, and this signal is provided to computer 22 that includes a time input to provide a rate of change of frequency determination section 24. The rate of change of frequency (df/dt) is a function of liquid water content, air temperature and airspeed and is determined in a matter of milliseconds during initial ice accretion, and updated continually until the deicing heaters are turned on. The heaters can be turned on at a selected time after an initial df/dt signal, or when df/dt reaches a selected value. The probe heaters remain on long enough to deice the probe after which the cycle repeats. The correlation of the frequency rate change signal to LWC can be provided in a look up table shown at 26, or by entering the parameters into an algorithm in memory section 26A of the computer 22. Based upon temperature and airspeed inputs, and the measured rate of change of frequency over all or a portion of the ice accretion cycle as shown in Figures 2, 3 and 4, the liquid water content (LWC) measurement can be determined.

The look up tables or algorithm reflecting the measured plots include an input of the true air speed 28. For example, an input from a pitot tube, or

-8-

other suitable air speed indicator, that determines the relative velocity of the airflow 18 past the vibrating probe 12 may be used. An additional input parameter is air temperature indicated at 30, which
5 can be obtained from a known total air temperature sensor, or an ambient air temperature sensor, as an input to the look up table 26 or algorithm section 26A.

Air vehicle configuration constants,
10 including for example the aircraft tolerance to ice build up can be an input, as indicated at 27. These factors can insure timely activation, while minimizing nuisance activation, of ice protection equipment, and also can insure a more correct LWC indication.

15 The known relationship of the liquid water content to the rate of change of frequency, air speed and air temperature, and if desired, aircraft configuration constants, then will provide a signal that is a direct, reliable indication of liquid water
20 content (LWC) as indicated at 32. This LWC information can be used for research or analysis of the ambient air. Additionally, the output of the look up table and computer 22 can be utilized for activating the probe heater 20, as shown by a signal
25 along the line 34, and also can then be used for activating and turning on the air vehicle surface deicing heaters indicated at 36 and/or notifying the crew of an icing condition, which comprise one form of ice protection system.

30 Utilizing a vibrating type ice detector, and using known air temperature and airflow velocity, in one plot a temperature of -5°C, and an air velocity of 200 knots, the results at three different levels of

-9-

LWC are plotted in Figure 2. It can be seen that at the known LWC levels of 0.3, 0.75 and 1.2 grams per cubic meter, indicated by the plots 40, 42 and 44, respectively, the rate of change of resonant vibration frequency of the ice detector probe as ice accretes on the detector probe provides an indication of the liquid water content that can be identified quickly. The elapsed time is very short before distinct patterns emerge. For example, within 10,000 milliseconds a determination of the rate of change in frequency in Hertz per millisecond can be examined and determined from the plotted data points. At 20,000 milliseconds the data for each LWC merge and the plots are clearly defined. From commencement of accretion to about 5,000 milliseconds the data points run together and are somewhat scattered. The plots or curves are derived using air samples with a known LWC. All of the liquid water content (LWC) samples used in plotting Figure 2 have a liquid water content that is above the Ludlam Limit at the temperature and airflow rates disclosed.

The heaters for deicing the ice detector probe 12 are turned on at the ends of the plots in Figures 2, 3 and 4. For example, the probe heaters are turned on at the time represented by vertical lines 45 and 46 in Figure 2 for the plots at 0.75 and 1.2 grams per cubic meter, and are turned on at the time shown by vertical line 48 for 0.3 grams per cubic meter. The heater turn on signal is given when the ice has built up on the probe to affect the frequency signal from the probe a desired amount.

Identifiable results are also achievable with a lower ambient air temperature, -10°C, as

-10-

illustrated in Figure 3, and at the same air velocity of 200 knots. The plots for 0.3, 0.75 and 1.25 grams per cubic meter are indicated at 50, 52 and 54, respectively. The measured data points for each LWC
5 merge closely together to define distinct identifiable plots of df/dt in less than 10,000 milliseconds to provide an indication of the liquid water content (LWC), regardless of whether the content is above the Ludlam Limit. In Figure 3, (-10°C and 200 knots) only
10 .75 and 1.2 g/m³ plots exceed the Ludlam Limit of LWC.

Again, the probe heaters are turned on where the plots end in Figure 3, generally along a vertical line 58, for the plots where the LWC is above the
15 Ludlam Limit, namely plots 52 and 54, and a vertical line 56 for the turning on of the deicing heater on the vibrating type deicer probe when the LWC is below the Ludlam Limit, namely 0.30 g/m³.

Figure 4 shows further plots of the rate of
20 change of frequency in hertz per millisecond plotted against time, in milliseconds. In this case, the temperature is -5°C and airspeed is 100 knots. While somewhat more scattered, the data points can be averaged so that the plots for the liquid water
25 content (LWC) of 0.30 g/m³, is shown at 60. The .30 g/m³ LWC is below the Ludlam Limit while the others are above the limit. The plot for 0.75 g/m³ is indicated at 62, and the plot for an LWC of 1.20 g/m³ is indicated at 64, these plots all show that the rate of
30 change of frequency, df/dt provides sufficient information to indicate the liquid water content (LWC) within about 15,000 milliseconds with reliability. Again, in this instance, the heaters are turned at a

-11-

time indicated by vertical lines 66 and 68 for the plots of 0.75 and 1.20 g/m³, respectively, and the heaters are turned on for the plot for the 0.30 g/m³ at the time line 70.

5 The rate of change of frequency df/dt , will provide information indicating the rate of ice accretion in each of the plots, even though the liquid water content (LWC) may be above the Ludlam Limit. This can provide for early information to the crew of
10 an icing condition and/or activation of the deicing heaters on the air vehicle to avoid any substantial build up of ice. Also, the information on LWC can be used for research and analysis because the present invention gives a reliable indication of liquid water
15 content at substantially all ranges of liquid water content.

Figure 5 is a plot of df/dt averaged data points for different airspeeds to show that there are distinct indications of liquid water content at
20 different air speeds, different liquid water content amounts, and different temperatures such that LWC can be determined reliably.

The points on the plot are derived from an average of approximately 20 data point readings near
25 the ends of the plots for corresponding LWCs shown in Figures 2, 3 and 4, as well as similar data points taken at different airspeeds and temperatures as listed in Figure 5. For example, at a temperature of -5°C, three plots are provided for liquid water
30 contents of 0.3, 0.75 and 1.2 g/m³. Each of these conditions of temperature and known liquid water content were used to determine df/dt of a vibrating probe at airflows of 100, 150 and 200 knots.

-12-

The plot shown at 60 is with 0.30 g/m^3 of liquid water at -5°C , and at 100, 150 and 200 knots. The change in rate of change of frequency (df/dt) does not show wide swings, but shows definitive changes
5 between the air flows to indicate liquid water content at particular air speeds and temperature based upon the rate of change of frequency.

Plot 62 represents data points for df/dt at -5°C and 0.75 g/m^3 liquid water content, and shows
10 greater changes between the listed air speeds.

The plot 64 is for -5°C with a liquid water content of 1.2 g/m^3 . Again, the rate of change of frequency provides a distinctive signal at each of the various air speeds to permit direct indication of
15 liquid water content.

At -10°C , the 0.3 g/m^3 liquid water content measuring df/dt results in a plot 66; the 0.75 g/m^3 LWC results in a plot 68, and the 1.2 g/m^3 LWC provides a plot 70. Again, the individual points shown for the
20 plots 60, 62, 64, 66, 68 and 70 are averages of df/dt of data points taken shortly before the heater is turned on, or near the right hand end of the plots of data points shown in Figures 2, 3 and 4.

In aggregate, the plots of Figure 5 show
25 that definitive points are established at each air speed, temperature, and df/dt condition, so that upon determining the rate of change of frequency after a selected time from the start of ice accretion, the liquid water content at a particular temperature and a
30 particular air speed can be determined by a lookup table or by an algorithm. The look up table values can be extrapolated for different airspeeds and temperatures, so knowing df/dt the LWC can be

-13-

determined. Also df/dt can give the desired information on when to turn on the heaters.

The present invention thus uses readily available information for providing the liquid water content (LWC) of airflow past a vibrating type probe such as an ice detector probe. The determination of the rate of change of frequency is a straight forward computation based upon the change in frequency across a time measurement. The discovery that the rate of change of frequency of a vibrating type ice detector probe provides reliable indications of liquid water content (LWC) at substantially all useful ranges of such liquid water content (LWC) in ambient air permits enhanced operation of air vehicles in particular, insofar as deicing equipment is concerned, and enhances the ability to make LWC measurements of reasonable quality for research purposes.

The indication of LWC is reliably obtained, even when the LWC is above the Ludlam Limit.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

-14-

WHAT IS CLAIMED IS:

1. An apparatus for determining the liquid water content in an airflow, comprising a vibrating probe excitable to vibrate at a resonant frequency which changes as ice accretion occurs, a frequency determination circuit for determining the frequency of vibration of the ice detector probe, and for calculating rate of change of such frequency, and for correlating the rate of change of frequency with inputs including air velocity and air temperature to provide an output indicating liquid water content.
2. The apparatus of claim 1 including probe deicing heaters connected to receive the output signal for activating the heaters at selected times.
3. The apparatus of either of claims 1 or 2 wherein the liquid water content is above the Ludlam Limit.
4. A method of determining liquid water content in an airflow, including providing a vibrating ice detector probe, determining frequency changes indicating ice accretion on the probe, determining the rate of change of frequency of the probe as ice accretes, and providing the rate of change of frequency as an output indicating liquid water content of the air.
5. The method of claim 4 including the step of initiating heaters on the ice detecting probe after a selected time.
6. The method of either one of claims 4 or 5 including the step of initiating ice protection systems on an air vehicle on which the probe is mounted.

-15-

7. The method of either one of claims 4 or 5 including determining liquid water content by providing a measured temperature of the airflow, and the velocity of airflow to a processor including circuit for determining rate of change of frequency.

8. The method of claim 7 including providing aircraft configuration constants to the processor.

9. An apparatus for determining the liquid water content of air at a known temperature below the freezing point of water and at a known airspeed, including a vibrating probe excited to a resonant frequency on which supercooled water in the air can freeze and accrete, and a frequency determining circuit connected to the probe to provide an indication of rate of change of frequency of vibration as ice accretes.

10. The apparatus of claim 9 and a computer to receive the indication of rate of change of frequency of vibration of the probe and to compare the rate of change to values in a look up table to determine liquid water content of the air.

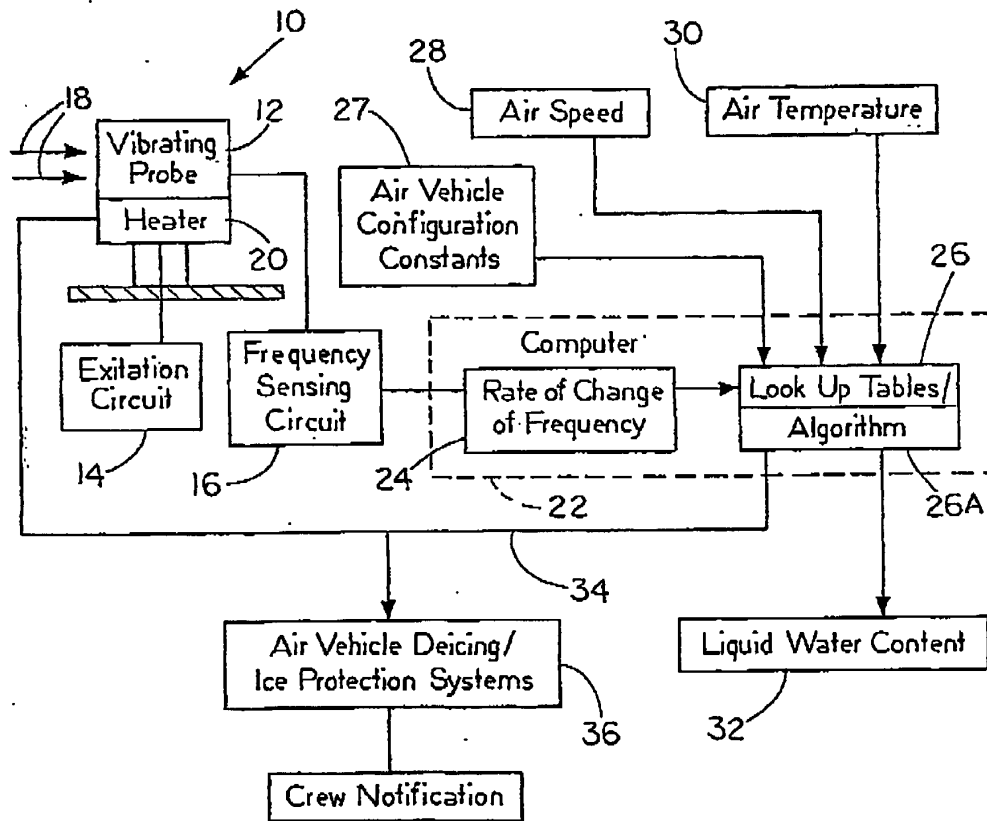
11. The apparatus of claim 9 and a computer having a memory with an algorithm to receive inputs comprising air temperature and air velocity past the probe and the indication of rate of change of frequency and to provide a value of liquid water content of the air.

12. The apparatus of any one of claims 9, 10 or 11 wherein the inputs to the computer include aircraft configuration constants.

-16-

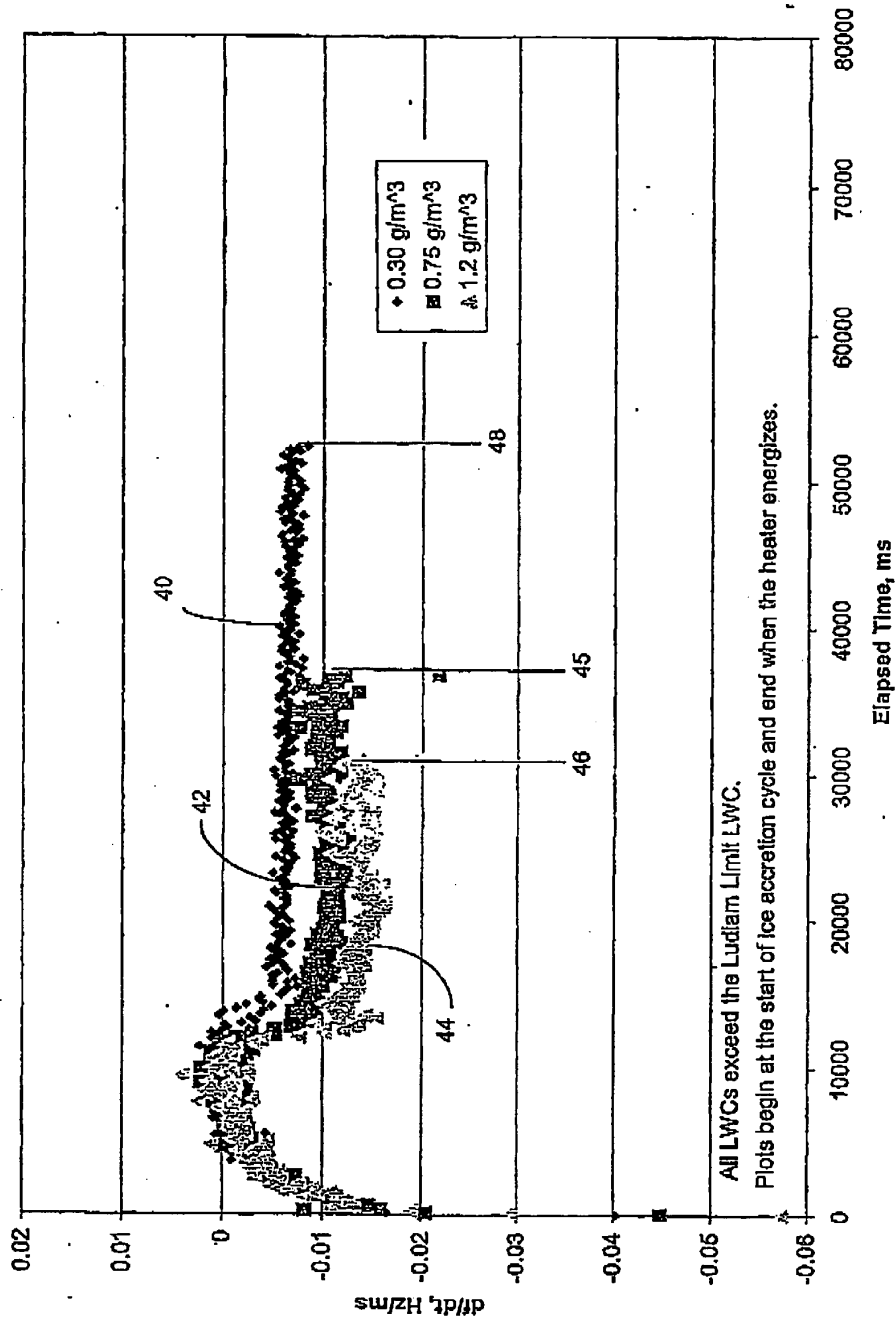
13. The apparatus of any one of claims 9-12 wherein a processor receives inputs indicating air temperature and air velocity at the probe, comprising the known temperature and the known airspeed, and the rate of change of frequency to provide the indication of liquid water content of the air.

FIG. 1



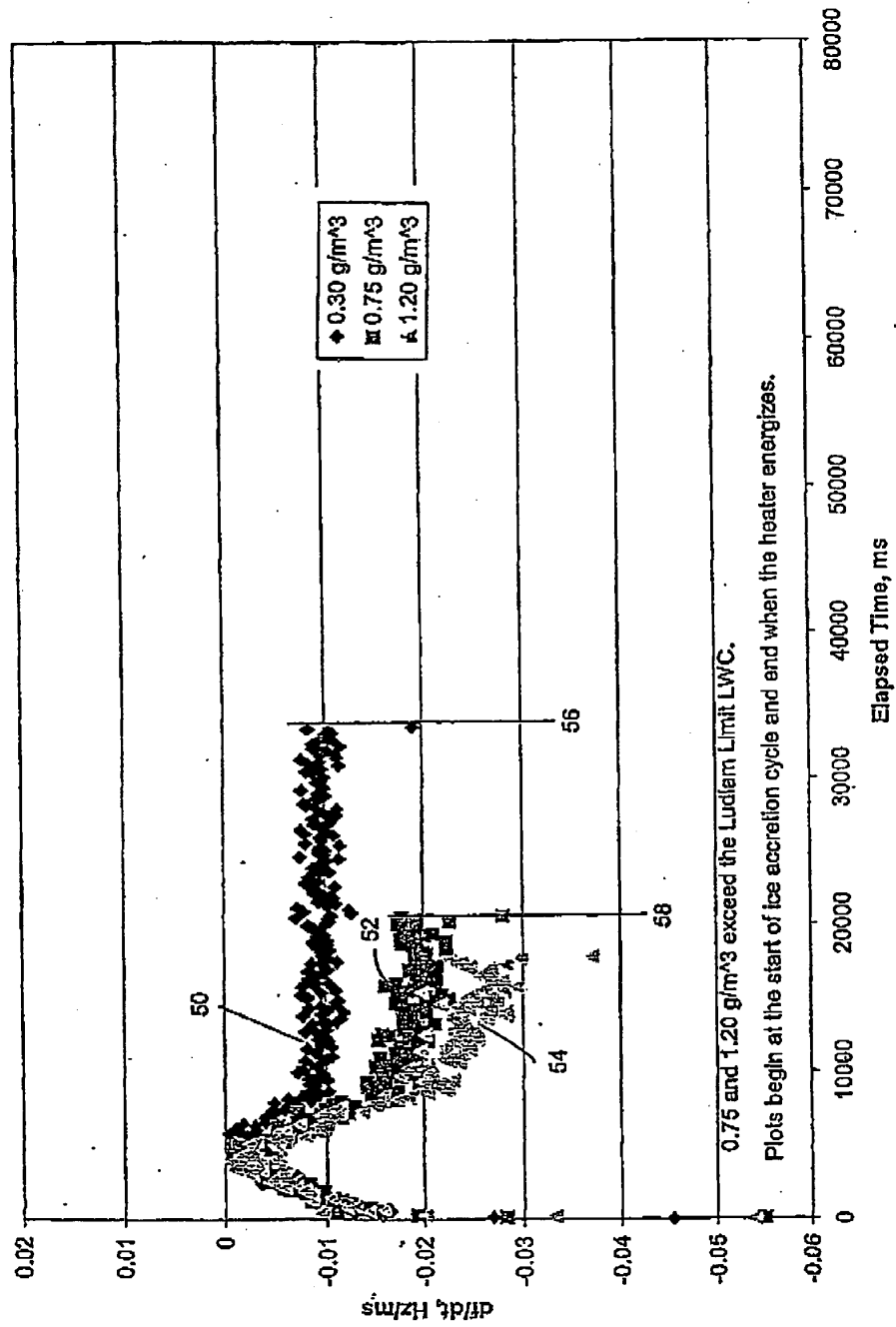
df/dt During Ice Accretion
at -5°C Ts, 200KTS

Figure 2



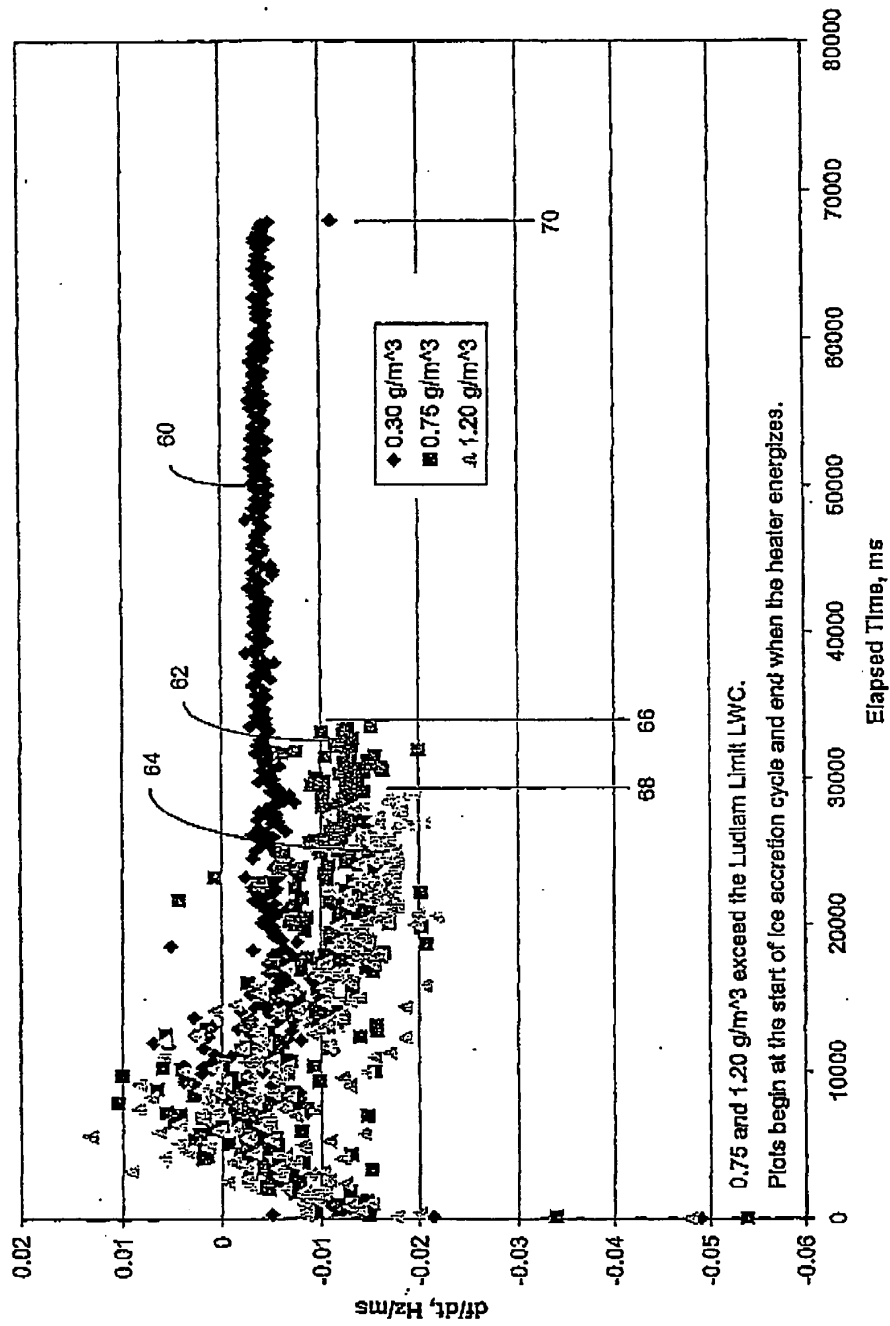
df/dt During Ice Accretion
-10°C Ts 200KTS

Figure 3



df/dt During Ice Accretion
-5°C Ts, 100KTS

Figure 4



| A. CLASSIFICATION OF SUBJECT MATTER IPC 7 B64D15/22 | | |
|--|---|--|
| According to International Patent Classification (IPC) or to both national classification and IPC | | |
| B. FIELDS SEARCHED | | |
| Minimum documentation searched (classification system followed by classification symbols) IPC 7 B64D | | |
| Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched | | |
| Electronic data base consulted during the international search (name of data base and, where practical, search terms used) EPO-Internal, COMPENDEX, WPI Data, PAJ | | |
| C. DOCUMENTS CONSIDERED TO BE RELEVANT | | |
| Category * | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
| A | ROY S ET AL: "Smart ice detection systems based on resonant piezoelectric transducers" SENSORS AND ACTUATORS A, ELSEVIER SEQUOIA S.A., LAUSANNE, CH, vol. 69, no. 3, 15 September 1998 (1998-09-15), pages 243-250, XP004140047 ISSN: 0924-4247 | 1,2,9,11 |
| X | page 248, column 2, line 4 - line 25 | 4 |
| A | US 4 570 881 A (LUSTENBERGER MARTIN) 18 February 1986 (1986-02-18) column 1, line 29 - line 51 | 1,4,9 |
| A | US 5 932 806 A (HAMMER JEFFREY MARK ET AL) 3 August 1999 (1999-08-03) column 6, line 5 - line 33 | 1,4,9 |
| -/- | | |
| <input checked="" type="checkbox"/> Further documents are listed in the continuation of box C. <input checked="" type="checkbox"/> Patent family members are listed in annex. | | |
| * Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art. "&" document member of the same patent family | | |
| Date of the actual completion of the international search 3 January 2002 | | Date of mailing of the international search report 09/01/2002 |
| Name and mailing address of the ISA European Patent Office, P.B. 5618 Patentlaan 2 NL - 2280 HV Rijswijk Tel (+31-70) 340-2040, Tx 31 651 epo nl Fax (+31-70) 340-3016 | | Authorized officer Hauglustaine, H |

Form PCT/ISA/210 (second sheet) (July 1992)

| Patent document cited in search report | | Publication date | Patent family member(s) | Publication date |
|---|---|---------------------|----------------------------|---------------------|
| US 4570881 | A | 18-02-1986 | CA 1250926 A1 | 07-03-1989 |
| | | | CH 656015 A5 | 30-05-1986 |
| | | | EP 0229858 A1 | 29-07-1987 |
| | | | JP 1845470 C | 25-05-1994 |
| | | | JP 5056831 B | 20-08-1993 |
| | | | JP 62132148 A | 15-06-1987 |
| | | | SU 1521294 A3 | 07-11-1989 |
| | | | AT 43731 T | 15-06-1989 |
| | | | DE 3570777 D1 | 06-07-1989 |
| US 5932806 | A | 03-08-1999 | US 5629485 A | 13-05-1997 |
| | | | AU 4639996 A | 03-07-1996 |
| | | | CA 2206941 A1 | 20-06-1996 |
| | | | EP 0797773 A1 | 01-10-1997 |
| | | | JP 10510627 T | 13-10-1998 |
| | | | WO 9618894 A1 | 20-06-1996 |
| EP 0600357 | A | 08-06-1994 | AU 5205793 A | 09-06-1994 |
| | | | CA 2110188 A1 | 31-05-1994 |
| | | | CN 1094812 A | 09-11-1994 |
| | | | EP 0600357 A1 | 08-06-1994 |
| | | | US 5686841 A | 11-11-1997 |
| | | | ZA 9308891 A | 29-05-1995 |
| US 3341835 | A | 12-09-1967 | DE 1573295 A1 | 09-04-1970 |
| | | | GB 1087475 A | 18-10-1967 |

Form PCT/ISA/210 (patent family annex) (July 1992)

| C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT | | |
|--|--|-----------------------|
| Category * | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
| A | EP 0 600 357 A (RIM TECH INC) 8 June 1994 (1994-06-08) page 3, line 40 -page 4, line 11 | 1,4,9 |
| A | "ANNOUNCEMENT" AVIATION WEEK AND SPACE TECHNOLOGY, MCGRAW-HILL INC. NEW YORK, US, vol. 142, no. 24, 12 June 1995 (1995-06-12), page 59 XP000510920 ISSN: 0005-2175 the whole document | 1 |
| A | US 3 341 835 A (WERNER FRANK D ET AL) 12 September 1967 (1967-09-12) cited in the application the whole document | 1 |

Form PCT/ISA/210 (continuation of second sheet) (July 1992)